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GAMMA-GAMMA DIRECTIONAL CORRELATIONS IN Pr^{144}

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ABSTRACT. The gamma rays of energy region 34-100 keV, following the beta decay of Ce^{144}, have been studied using coincidence and directional correlation methods, taking care of the highly disturbing scattering effects in this region. The correlation function found for the 54-80 keV cascade supports the spin assignment of 0^- for the Pr^{144} ground state. It is further shown that the direct angular correlation measurement of the 34-100 keV cascade cannot lead to any unambiguous spin assignment of the ground state.

INTRODUCTION

The spin of the Pr^{144} ground state has been the subject of considerable controversy in recent years. 0^- spin and parity assignment was made to this state in the level scheme (Fig. 1) of Pr^{144} deduced by Geiger *et al.* (1960) from a careful measurement of the conversion electron spectrum and the conversion line intensity ratios following the beta decay of Ce^{144}. This was later supported by conversion electron-gamma and gamma-gamma coincidence studies (Geiger et. *al.*, 1961) of the Pr^{144} gamma transitions. Several other authors (Raghavan and Steffen, 1963; Porter and Day, 1959; Hess *et al.*, 1963), on the basis of studies of the beta-gamma directional correlation and the beta spectrum shape in the Pr^{144}—Nd^{144} decay, have also confirmed the 0^- spin assignment. On the other hand, the results of the beta-gamma circular polarization and directional correlation measurements (Graham *et al.*, 1958; Eman and Tadic, 1963; Hess *et al.*, 1963; Collin *et* al., 1963; Lobashov and Nazarenko, 1961) in the Pr^{144}—Nd^{144} decay do not completely rule out an 1^- spin for the ground state of Pr^{144}. The whole situation has been carefully analysed by Singru *et al.* (1963) who conclude : "No unique spin assignment to the Pr^{144} ground state is possible on the basis of the available measurements on the Pr^{144}—Nd^{144} beta-transitions. A unique spin assignment to the Pr^{144} ground thate is possible, however, if the available experimental data on the beta and gamma transitions in the Ce^{144}—Pr^{144} decay are properly interpreted". Moreover, controversy existed also about the spin of the 134 keV excited state of Pr^{144}, as the beta decay data (Hickock *et al.*, 1958) allowed three spin values, namely, 0, 1 and 2. A spin assignment of 1^- to the 134 keV excited state has been possible now from Geiger's decay scheme (Fig. 1) as well as from the beta-

gamma directional correlation measurements made by Collin *et al.* (1963), following the Ce^{144} beta decay.

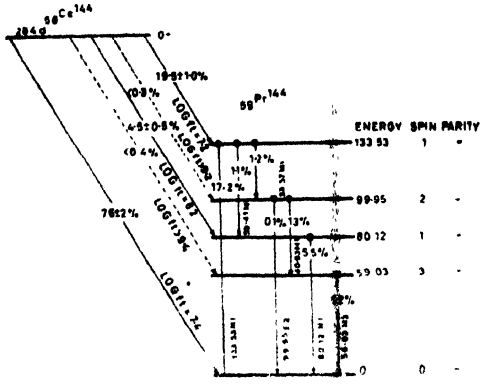

Fig. 1. Decay scheme of Ce^{144} as proposed by Geiger et al.

The two gamma-gamma cascades following the Ce^{144}—Pr^{144} decay, namely, 34-100 keV and 54-80 keV both involve the ground state as well as the 134 keV excited state of Pr^{144}. The 80 and the 100 keV gamma transitions feed the ground state of Pr^{14}(Fig. 1) and are expected to be pure multipoles, if the ground state spin were to be 0^-. From the internal conversion studies of Geiger *et al.* (1960, 1961), it is clear that the 80 keV transition is >99% M1. As regards the 100 keV transition, the internal conversion measurements (Geiger *et al.*, 1960; Geiger *et al.*, 1961), though consistent with its pure E2 character, do not rule out the possibility of an appreciable M1 admixture (~ 25%) in this transition.

The original aim of this work was to analyse the multipole mixing of the 100 keV transition by carrying out the gamma-gamma directional correlation of the 34-100 keV cascade, for which very scanty data (Bhattacharyya and Shastry, 1963) exist at present. This would also calrify the ground state spin of Pr^{144}. Strongly interfering coincidence counts from this energy region and the extremely low intensity of the 100 keV transition, however, made such a measurement inconclusive. The results of our coincidence and directional correlation measurements on this cascade as well as those of other authors (Sengupta *et al*, 1959; Bhattacharyya and Shastry, 1963) are discussed here and their inconclusive character brought out. Alternatively, we considered it worthwhile to examine the ground state spin of Pr^{144} from the gamma-gamma directional correlation measurement of the 54–80 keV cascade, which has so far been investigated only by Zuk *et al.* (1963). This measurement promises to decide finally the spin and parity assignment to the Pr^{144} ground state.

EXPERIMENTAL PROCEDURE

The gamma ray scintillation spectrum of Ce^{144} is shown in Fig. 2. A perspex disc of suitable thickness was interposed in front of the crystal to reduce beta

contribution from the decay of Pr^{144}. All coincidence measurements were carried out using a fast-slow coincidence assembly with an effective resolving time of

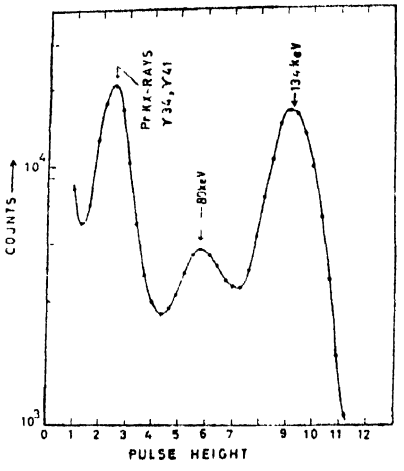

Fig. 2. Gamma ray scintillation spectrum of Ce^{144}.

$\approx$ 30 ns. The coincidence spectra are recorded by setting one spectrometer first on the 34 and then on the 80 keV region. The results of the gamma-gamma coincidence and the gamma-gamma directional correlation measurements of the 54-80 keV cascade are discussed in the following sections.

GAMMA-GAMMA COINCIDENCE MEASUREMENTS

The observed gamma ray spectrum coincident with the Pr K X-rays ($\sim$35 keV) is shown in Fig. 3. The spectrum is similar to that obtained by Sengupta et al. (1959). It shows a strong peak at 100 keV of intensity comparable to that of γ-80. The same spectrum recorded by Geiger *et al.* (1961), with properly shielded crystals, shows, however, an almost complete absence of a peak at 100 keV.

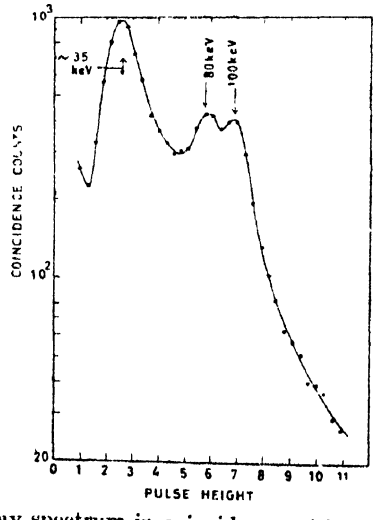

Fig. 3. Gamma ray spectrum in coincidence with the Pr *K* X-rays.

The computed relative photopeak intensities in this coincidence spectrum based on their decay scheme (Fig. 1), assuming that the gate includes the Pr K X-rays, γ-34 and γ-41, are in reasonable agreement with their observed coincidence scpectrum. The computed relative photopeak intensity expected at 100 keV is only $\sim$4% of the observed photopeak intensity at 80 keV and is not expected to be resolved in the spectrum. The relatively strong peak at 100 keV in the coincidence spectrum observed in the present work and that of Sengupta *et al.* (1959) is, therefore, not explained. It may presumably arise as a result of the contribution from (a) the Compton scattering of the 134 keV quanta from one crystal to the other, (b) the escape of the Iodine K X-rays from one crystal to the other and (c) the neighbouring peak at the 80 keV. The presence of interfering coincidences due to (a) is directly confirmed by us by taking a Ce^{144} source and observing that false coincidences are produced by Compton scattering of its 142 keV gamma ray at the same channel settings as in the actual experiment.

It is clear that with the two counters mutually shielded from each other, the actual number of 34-100 keV coincidences would indeed be exremely small because of the very weak intensity of the 100 keV transition. Consequently, these would not be resolved in the coincidence spectrum in the presence of the strong neighbouring peak at 80 keV.

The directional correlation of the 34-100 keV cascade has been measured by Bhattacharyya and Shastry (1963) who seem to have observed a measurable area under the 100 keV peak in the coincidence spectrum of the Pr K X-rays. The correlation function obtained by them is

$$W(\theta) = 1 - (0.226 \pm 0.030)\, P_2(\cos\theta) + (0.018 \pm 0.030)\, P_4(\cos\theta). \quad \ldots \quad (1)$$

The directional correlation measurement carried out by us for this cascade also showed an A_2 value $[-(0.270 \pm 0.038)]$ comparable to the above $[-(0.226 \pm 0.030)]$. The theoretical values of the expansion coefficients A_2 and A_4 for the 1(M1)2(E2)0 cascade are -0.250 and 0. respectively. These directional correlation results, therefore, apparently support a 0^- spin assignment to the Pr^{144} ground state and an E2 multipolarity of the 100 keV transition. Both these measurements, however, have been made without correcting for the various contributions to the coincidence counts as explained above. It is, therefore, difficult to attach any significance to these measurements, as the results obtained may arise almost entirely from the spurious coincidences expected in this energy region. We would rather conclude that a reliable measurement of the directional correlation of the 34-100 keV cascade is not feasible and thus nothing definite can be said about the multipole character of the 100 keV transition from this directional correlation experiment.

GAMMA-GAMMA DIRECTIONAL CORRELATION OF THE 54-80 keV CASCADE

Using double the voltage gain to allow adequate separation between the various gamma rays, the observed gamma spectrum coincident with the γ-80 is reproduced in Fig. 4 The estimated shape of the 54 keV gamma line is also indicated by the dashed line in this figure. The broadening of the K X-rays photopeak on its higher energy side seems to indicate the contribution of Compton scattering of the 134 keV quanta.

For measuring the directional correlation of the 54-80 keV cascade, one of the spectrometers was set on the lower half of the 80 keV photopeak and the other on the high energy side of the 54 keV peak, as obtained in the coincidence spectrum of Fig. 4. The windows thus selected are intended to suppress almost

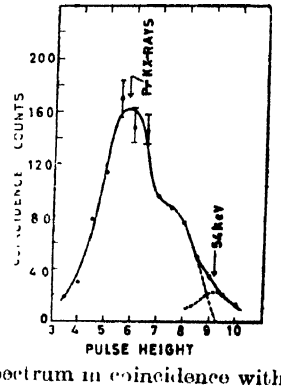

Fig. 4. Gamma ray spectrum in coincidence with the 80 keV photopeak.

completely the effect of Compton scattering of the 134 keV quanta. The interference from the neighbouring Pr K X-rays peak (Fig. 4) is thereby also eliminated. A test coincidence measurement carried out with a Ce^{141}—source at these window settings proved the effectiveness of protection against the spurious coincidences due to Compton scattering.

The data were collected at 90°, 135°, 180° 225° and 270° with respect to the fixed detector in a total of ~ 50 counting hours. The normalized expansion coefficients, after correcting for finite angular resolution, are :

$$A_2 = -0.168 \pm 0.030, \qquad A_4 = 0.022 \pm 0.077. \qquad \ldots (2)$$

As already stated, the spin of the 134 keV state of Pr^{144} is convincingly established as 1^- from the available experimental data (Geiger *et al.* 1961; Collin *et al.* 1963). We also know that all the gamma transitions in Pr^{144}, with the exception of γ-59 and γ-100, are M1 transitions with less than 1% E2 admixture. As explained earlier, the ground state spin of Pr^{144} can be either 0^- or 1^-. Three possible spin sequences for the 54-80 keV cascade then follow. Assuming ~1% E2 admixture in both the 54 and the 80 keV transitions, the probable limits of

the expansion coefficient A_2, computed theoretically, corresponding to the three possible spin sequences are as follows :

(i) $1(D, Q)\, 1(D)0 \rightarrow \quad -0.37 < A_2 < -0.08,$

(ii) $1(D, Q)1(D, Q)1 \quad +0.016 < A_2 < +0.28,$

(iii) $1(D, Q)2(D, Q)1 \quad +0.09 < A_2 < +0.36.$

where D and Q denote the dipole and quadrupole contents in a transition. The experimental $A_2 = -(0.168 \pm 0.030)$ value, obtained by us, is only consistent with the spin sequence (i) and provides a most convincing evidence for a 0^- ground state spin assignment of Pr^{144}. Conclusions drawn earlier by Zuk *et al.* (1963) from the directional correlation measurement of this cascade also fabour a 0^- spin assignment. Their experimental value $A_2 = -(0.102 \pm 0.020)$ is also compatible only with the spin sequence (i).

CONCLUSION

It is thus possible to make an independent check of the ground state spin assignment of Pr^{144} from the gamma-gamma directional correlation of the 54-80 keV cascade only. The 34-100 keV cascade leads to inconclusive results. Also the contradiction existing in the gamma ray spectrum in coincidence with the Pr K X-ray observed by Geiger *et al.* (1961) and by Sengupta *et al.* (1959) is explained.

Geiger *et al.* have tried to explain the 0^- ground state spin of Pr^{144} on the theoretical grounds. Although the situation is quite complex in odd-odd nuclei, they have proposed an interpretation on the unified model in terms of the intrinsic odd nucleon level assignments of Mottelson and Nilsson, which seems to account at least qualitatively for the said ground state spin assignment.

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